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1 Enhancing frequency stability by integrating
2 non-conventional power sources through multi-terminal
3 HVDC grid

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10 **Abstract**

The 2050 targets established by the EU will foster both larger penetration of renewable energy, especially wind power, and more cross-border interconnections. Moreover, this new framework requires the non-conventional power sources and power converter-based systems to be responsible for the duties traditionally carried out by conventional synchronous generators as frequency support. This paper presents how different power-electronic based technologies can provide frequency support individually and in a coordinated manner (with different priority given by the deadbands) ensuring a stable operation. The implemented scenarios examine challenging conditions, where the primary reserve of the interconnected conventional, renewable, and storage generation is fully utilized to tackle frequency incidents. This demonstrates how the joint regulation of the power electronic-based technologies enhances the frequency stability of the AC synchronous areas. The different control schemes and their interaction are investigated in Cigré DC grid benchmark adapted for frequency stability studies and implemented in Matlab/Simulink simulation tool. This modified grid includes 5-terminal HVDC grid with two offshore wind farms and three AC networks including battery and onshore wind farms.

11 **Keywords:** wind power, HVDC transmission, multi-terminal HVDC grid,
12 energy storage, frequency support, ancillary services

1. Introduction

The European Union (EU) has pushed towards the full decarbonization of the energy systems with the targets and plans set for 2050, which aim to reduce the greenhouse gas emission levels of 1990 by 80-95% [1]. It is expected that this objective will foster the electricity generation share of renewable energy sources up to 100% [2]. The European Wind Initiative (EWI) foresees that, under this green scenario, wind energy supply about 50% of Europe electricity needs [3].

To achieve such penetration level, wind power plant installations have to continue increasing. The current trend is to develop larger, in both size and ratings, wind turbines and to install them offshore due to less space restrictions and better wind conditions [4]. In addition, offshore wind farms are moving to farther locations with distances longer than 100 km from shore [5].

According to these changes, high voltage direct current (HVDC) transmission technology become an attractive option. For long distances and large amount of transmitted power, HVDC is a strong competitor compared to conventional high voltage alternate current (HVAC) [6]. In order to allow larger penetration of offshore wind power (and renewables in general) into the power system, more interconnection and power sharing capability between different countries are required (e.g. SuperGrid concept [7]). Thus, taking advantage of offshore wind power and the HVDC technology, multi-terminal HVDC networks can be integrated to make it real [8]. As an initial step, a HVDC link is planned to connect between Norway and Scotland (i.e. NorthConnect [9]).

The reduction of global inertia is one of the major barriers for power systems that is caused by the increased renewable energy penetration and the shutdown or replacement of conventional synchronous generators (e.g. nuclear) as well as the increment of generation connected through power electronic based systems (i.e. inverter-based, HVDC links, MultiTerminal-HVDC) and the installation of energy storage and FACTS which may help on ensuring stable and secure operation. This leads to a change in power system dynamics making the net-

work more vulnerable to frequency excursions. In order to mitigate that critical impact and keep the power system stable and secure, transmission system operators (TSOs) are developing novel grid codes with more restrictive and/or novel requirements to the generation (including wind) and power transmission systems (i.e. HVDC) [10–13]. These novel grid codes state that HVDC systems and any type of generation of a certain size (above 50 MW in continental Europe, 10 MW in Great Britain or 5 MW in Ireland) should provide frequency support [11].

Since wind power and HVDC systems are power-electronic-based technologies, they have the capability of fast active power regulation, making them suitable for primary frequency support becoming the first protective barrier to frequency instability. In this regard, wind power may provide such support to the grid by different ways depending on the time-frame objective. On one hand, supporting fast primary response by delivering the kinetic energy naturally stored in the rotating masses within the wind turbine (i.e. inertia response) [14–16]. On the other hand, supporting slow primary response by either maintaining certain power reserves on wind turbines through de-loading or over-speeding control techniques [17–19], or coordinating wind farm response with energy storage systems [20, 21]. In the HVDC based systems, the transmission network may contribute to frequency support through modifying the power sharing among the different stations [22–24] or by trying to take advantage of the existing energy stored within the capacitors of the DC side, which could act as DC grid inertia [25, 26].

This paper integrates different theoretically-mature frequency support methods from wide range of conventional power sources and non-conventional power electronic based technologies including onshore and offshore wind power, battery energy storage and MT-HVDC. Thus, the interactions between the responses of these controllers are examined and compared. The key contribution is to show the need of potential coordination between different controllers that have the same major objective, because if they act simultaneously it could jeopardize their responses. The available control methods are modified to produce

73 a simplified picture of the proposed coordination and its impact on frequency
 74 stability. For example, properly tuned deadbands could maintain reasonable
 75 coordination and prioritization relying on the profile of each technology (i.e.
 76 available power reserve, speed of response, control methods and parameters).
 77 The applied case studies have been developed to compare the integration and
 78 coordination levels between different generation assets and controllers that are
 79 able to provide frequency support. The proposed control methods acknowledge
 80 the operation limits of different elements (e.g. BESS state of charge, converter
 81 stations capacities, available primary reserve, etc.).

82 In addition, a supplementary controller is developed to enable the battery
 83 energy storage system (BESS) to respond to the abrupt changes in power de-
 84 livery across the MT-HVDC grid. To improve the credibility of the obtained
 85 results different communication delays are applied, as well as severe scenar-
 86 ios (e.g. very steep wind speed drops and low available stored energy) are
 87 thoroughly investigated. This paper focuses on frequency stability, the control
 88 methods are dedicated to provide and enhance frequency support. The analysis
 89 of system response to other types of faults and stability issues is out of scope.
 90 However, the holistic control method of the MT-HVDC grid is capable of adapt-
 91 ing the requirements of the integrated systems because it is based on consensus
 92 theory. As an illustration, if a MT-HVDC converter station suffers a fault or
 93 one of the dc lines is lost, the control will modify autonomously the power ex-
 94 port/import set-points in all AC areas and wind farms trying to cope with the
 95 new operation conditions of the whole system. The proposed case studies are
 96 evaluated through dynamic simulations in a 5-terminal HVDC network based
 97 on the Cigré DC grid adapted for frequency stability studies. The model have
 98 been developed in Matlab/Simulink simulation tool. The implemented bench-
 99 mark accommodates two offshore wind farms that are connected to two stations
 100 of the MT-HVDC and three synchronous areas. In one AC grid a battery energy
 101 storage system is installed; whilst in another AC network an onshore wind farm
 102 is integrated.

103 2. Frequency support methods

104 In this section, the frequency support methods applied to different non-
105 conventional power sources including both onshore and offshore wind power
106 plants, BESS and MT-HVDC are explained.

107 2.1. Wind power plants

108 As previously stated, to enable the wind power plants to provide frequency
109 support an increment on active power generation is required. In particular, wind
110 power plants can provide primary frequency support through two main ways,
111 i.e. naturally stored kinetic inertia energy or maintaining certain reserve levels.
112 In this paper, two different wind turbines are integrated offshore and onshore
113 to investigate the interactions between WTGs from different manufacturers

114 2.1.1. Onshore wind power plants

115 The partial de-loading method is implemented to the onshore wind farm
116 (OWF) [18]. The partial de-loading method integrates two main concepts to
117 enable wind power to provide frequency support, namely, pitch de-loading and
118 kinetic energy extraction. This aims to minimize energy losses that occur due
119 to continuous de-loading. This method applies four operation regions according
120 to the incident WS as illustrated in Figure 1. In this paper, an average WS is
121 examined, hence, each WTG in the onshore WF in Area 2 is operating in region
122 2 under conventional pitch de-loading. This method does not rely on frequency
123 measurement to manage the amount of provided support power but only as a
124 trigger (i.e. activation-deactivation) signal. However, it requires rough estimate
125 of the incident wind speed to determine operational region and the potential
126 power reserves.

127 2.1.2. Offshore wind power clusters (OWPCs)

128 A continuous pitch de-loading approach is applied to OWPCs, where the
129 pitch angle is adjusted to keep a certain percentage of the available power as
130 reserve. A droop control is implemented to drive the supportive power surge

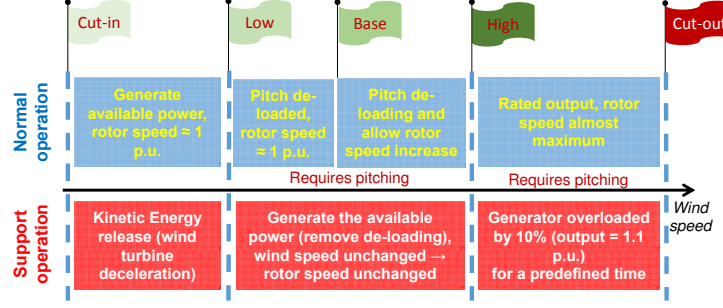
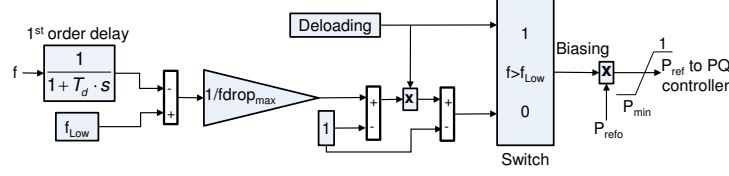


Figure 1: Simplified illustration of the partial de-loading method

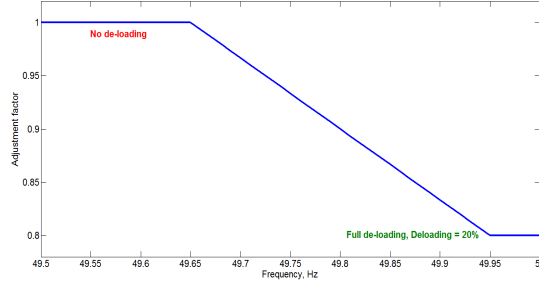
such that it is proportional to the frequency deviation, as shown in Figure 2(a). The frequency drop initiates a regulated removal of this de-loaded state until the frequency reaches a certain threshold where the wind turbine is already providing the total amount of available power to the grid, as can be seen in 2(b). The presumed de-loading ratio is widely discussed in literature [27, 28] and it also has economic implications, where the curtailed production will lead to reduced income, however, the financial aspects are not of interest to this paper. Conversely to the partial de-loading, this method needs the frequency measurement but allows intermediate power management. This method is seen as a better option for offshore wind because of the higher and more constant wind speed profiles compared to onshore sites.

2.2. Battery Energy Storage System (BESS)

The BESS carries out different tasks such as the provision of frequency support, coping with the power mismatch caused by OWPCs during short-time. It also provides the balancing power to the local area for fulfilling the increment change in the imported/exported power of each AC area or OWPC according to the set-points provided by the MT-HVDC frequency support controller. The control method applied is a developed version of the control proposed in [20], implementing a rate-of-change-of-frequency (RoCoF) and droop based frequency control and an export power deviation balancing support, as shown in Figure 3. In this paper, BESS controls have the capability of providing inertia



(a) Continuous droop control method diagram



(b) De-loading factor visualization

Figure 2: Frequency control method based on droop based continuous power de-loading

152 response (RoCoF based support power component) and primary response (fre-
 153 quency drop based component) to mitigate local frequency drops in the AC area
 154 where the BESS is integrated. Moreover, the BESS can provide export support
 155 relying on the control signal received from the MT-HVDC holistic controller to
 156 export power to other AC areas via the MT-HVDC. The size of the converter
 157 station of the AC area connecting it to the MT-HVDC is considered in the con-
 158 trol of the amount of the exported support power. The power deficits between
 159 the set-points of MT-HVDC controller and the actual outputs of both OWPCs
 160 and AC area are ΔP_{OWPC} and ΔP_{AC} , respectively.

161 The local support has higher priority and it is activated when the local fre-
 162 quency violates a certain deadband, and there is enough energy stored (State of
 163 Charge (SOC) $> SOC_{min}$). It is worth noting that after complying with the fre-
 164 quency deadband, the standby mode (i.e. no charging) is activated for a certain
 165 time to avoid any successive frequency drop. The later provides the balancing
 166 power to cover any deficit from the MT-HVDC setpoint and the actual power
 167 delivered by the OWPC. This includes a narrow tolerance (acceptable error)

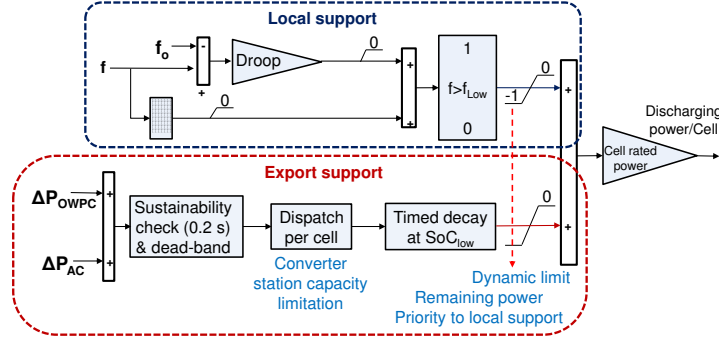


Figure 3: Schematic overview of the implemented BESS control

to avoid negative impacts on battery lifetime (cycling). Moreover, when the BESS reaches a certain threshold (close to SOC_{\min}), the provided power starts to decay with a fixed rate, such that no support is provided after few seconds. This should provide enough time for the other generation assets to balance the power requirements. The RoCoF-based controllers or the PD controllers in general might raise some issues, however, in the developed BESS controller the RoCoF-based supplementary controller is complemented with a deadband and it is used to confirm that the frequency drop is growing not a normal oscillatory response due to several system dynamics. This should have a positive impact on the lifetime of the BESS, since unnecessary discharging is mitigated.

2.3. Multi-terminal HVDC

The applied control scheme for providing frequency support by using the MT-HVDC is presented in [24]. The control scheme used in the MT-HVDC grid is a consensus-based algorithm, which is a multi-agent control, and aims to drive different active agents, the AC onshore areas, in our case, to achieve a common objective, which is minimizing the frequency deviations across the connected AC areas. To achieve this, the control redistributes the power mismatches at the different AC areas connected to the MT-HVDC until reaching a consensus on the frequency stability point. A simplified block diagram of the applied control

187 scheme is shown in Figure 4, where n and m are the numbers of AC areas
 188 and offshore WFs respectively, where $n = 3$, and $m = 2$. The main consensus
 189 controller parameters are alpha and beta with values are 20.76 MW and 8.6
 190 MWs respectively.

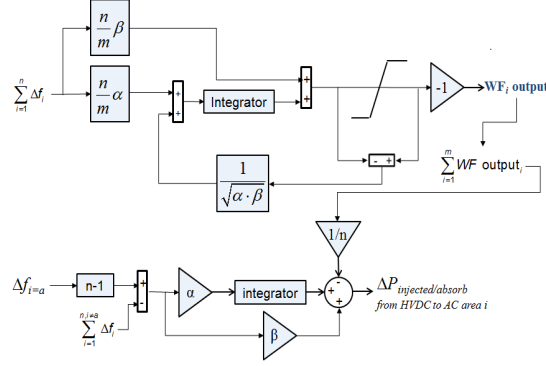


Figure 4: Simplified control scheme applied in [24]

191 The MT-HVDC controllers is the responsible of coordinate and distribute the
 192 support to be provided among areas and wind power to minimize the frequency
 193 deviation at any synchronous AC area. It is worth remarking that such control
 194 has information of all the converters existing at the MT-HVDC ensuring their
 195 adequate coordination.

196 3. Case studies and results

197 The different frequency support methods applied in the considered non-
 198 conventional technologies are tested through simulation in a well-accepted net-
 199 work based on the Cigré's HVDC grid benchmark [29]. This power system model
 200 is adapted for performing frequency stability studies. The network under study
 201 is illustrated in Figure 5. It includes a 5-terminal HVDC grid that connects two
 202 OWPC and three synchronous areas. Additionally, an OWF and a BESS are
 203 integrated in AC grids 1 and 2 respectively. The power transmitted is shared
 204 among the three interconnected areas according to the master voltage control
 205 method applied in this manuscript, which aims to achieve a balance between

the imported and exported power from/to the five converter stations connected to the MT-HVDC grid. This test system could be a provisional and simplified representation of the foreseen pan-European power system where different synchronous areas in Europe e.g. UK, Norway and the Netherlands are going to be interconnected through a MT-HVDC hub.

The main specifications considered for the synchronous generation areas under study are listed in Table 1 [22, 24].

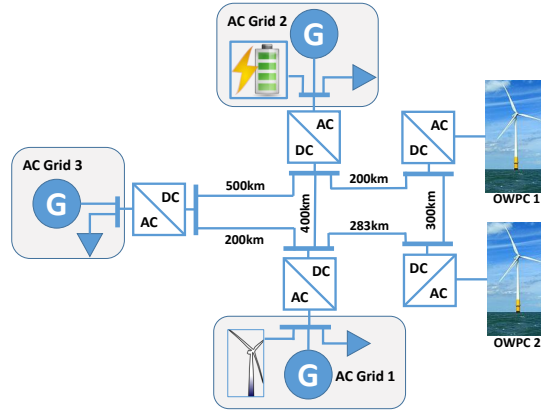


Figure 5: Simplified illustration of the MT-HVDC network under study

212

Different types of wind turbines are used for onshore and offshore wind power plants, i.e. 2 MW Gamesa's G90 wind turbine [30, 31] and the 5 MW NREL benchmark [32, 33] respectively. Thus, the interactions between different wind turbine technologies are analysed. Both OWPCs and OWFs are modelled as aggregated wind turbines. The BESS installed in AC area 2 is a Li-ion Battery based station modelled as in [20]. The parameters of the non-conventional power sources are given in Table 2, where P_{SG_nom} refers to the nominal power of the synchronous generator and J is its inertia.

The different study cases and scenarios to be considered for control performance comparison are presented. The paper analyzes five different study cases where different control strategies are activated in the same benchmark, during five different events which are illustrated in Figure 6. The events imitate real and

224

Table 1: The parameters of the integrated synchronous generation

	Area 1	Area 2	Area 3
P_{SG_nom} (MW)	60	60	150
Loading (%)		95	
J (kgm^2)	4863	4254	6485
SG Droop (%)	4	6	4
Time constant (s)	2	2	2.5
Load dyn. coeff.	95	140	145
Freq. Support	SG + BESS + OWPC	SG + OWF + OWPC	SG

225 highly possible bottlenecks that may be faced by power systems, namely genera-
 226 tion loss in both synchronous areas and offshore wind power plants due to wind
 227 speed drops. In practice, it is expected and assumed that each method has been
 228 developed independently without considering its integrative operation into the
 229 MT-HVDC where the holistic controller manages power sharing among different
 230 areas and wind farms. This could be the case when the MT-HVDC is applied
 231 in real world, where different generation assets with different control methods
 232 and parameters are integrated together. Moreover, the control of each system
 233 should mainly rely on the system where it is connected to mitigate the sophis-
 234 tication of the applied control method. Therefore, separate control design and
 235 parameter selection are considered and, the control parameters are not changed
 236 throughout all the cases. Due to the interactive operation of these controls,
 237 deadbands are applied. The deadbands are used as a simple coordination tool
 238 to prioritise the response of each element. Additionally, the MT-HVDC control,
 239 which is based on a consensus control provides power generation/consumption
 240 coordination among AC areas and wind farms. The consensus algorithm receives
 241 frequency variations in each area as inputs to drive their contributions.

Table 2: Non-conventional power sources parameters

BESS Stations	
Type	Li-Ion
Cell rated voltage (V)	48
Cell capacity (Ah)	11.45
Number of cells	7578
Initial SOC (%)	39
Total Rated Power (MW)	16.4
Total Energy (MWh)	5.5
Droop constant	75/f ₀
RoCoF gain	2
Wind Power Generation	
<i>OWPC 1 (MW)</i>	30
5 MW NREL WT (#)	6
<i>OWPC 2 (MW)</i>	40
5 MW NREL WT (#)	8
<i>Onshore WF (MW)</i>	60
2 MW G90 WT (#)	30

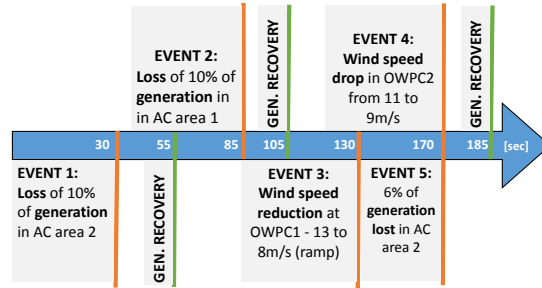


Figure 6: Simplified chronograph about the events considered in the study

Table 3: Frequency deadbands considered for each technology

Frequency drop deadbands (mHz)		
	BESS	20
	MT-HVDC	50
	OWPC	50
	Step 1: 25% ΔP_{wf}	30
OWF	Step 2: 50% ΔP_{wf}	45
	Step 3: 100% ΔP_{wf}	60

242 In the base case no frequency support is provided by any additional source,
 243 other than the local conventional synchronous generation. Case 1 refers to the
 244 provision of frequency support locally by some of the active power sources con-
 245 nected at each area as offshore wind, onshore wind and energy storage. Case
 246 2 considers only the joint contribution of MT-HVDC and OWPCs to provide
 247 frequency support to any area that suffers a frequency drop. In Case 3, the con-
 248 tribution of the energy storage to cover the gaps on the power delivered/required
 249 by the MT-HVDC at both the converter station and the OWPCs is included
 250 to the Case 2. Finally, Case 4 includes all the systems (i.e. BESS, onshore
 251 and offshore wind and the MT-HVDC) providing frequency support and power
 252 balancing at the same time.

253 Moreover, to make the cases closer to reality, different communication delays
 254 for both local and remote measurement and control signals are considered (15 ms
 255 and 30 ms, respectively), as well as different frequency response dead-bands
 256 depending on each technology and potential global impact, as shown in Table
 257 3. The dead-band values are selected based on grid code recommendations and
 258 limits [11].

259 3.1. Case 1: Local support provided by wind power and BESS

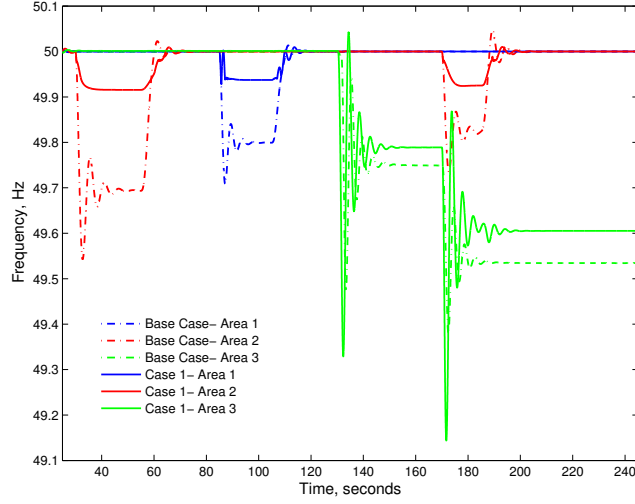
260 In this case only the provision of conventional local support is considered.
261 The MT-HVDC frequency support controller is still deactivated. However, the
262 set-point of active power reference at the converter station of the AC area facing
263 a frequency excursion is increased to accommodate the support power incoming
264 from the OWPC coupled to that area. The corresponding responses obtained are
265 plotted in Figure 7. As shown in Figure 7(a), the new steady-state frequencies
266 at each AC area are improved, compared to the base case, due to the additional
267 support provided by the local non conventional power sources illustrated in
268 Figures 7(b), 7(c) and 7(d).

269 Also, it is worth noting that the frequency nadir and the RoCoF of the
270 frequency responses in both Area 1 and 2 are better. Conversely, frequency
271 nadir and RoCoF of the Area 3 are worsened. This is because Area 3 acts as
272 master and it is the responsible of keeping voltage of MT-HVDC stable. Thus,
273 it suffered a larger power unbalance due to generation reduction without being
274 supported by any supplementary source. It must be remarked that the Base
275 Case and the Case 1 do not operate in the same steady state frequency because
276 of the existing power reserve from wind power used in Case 1.

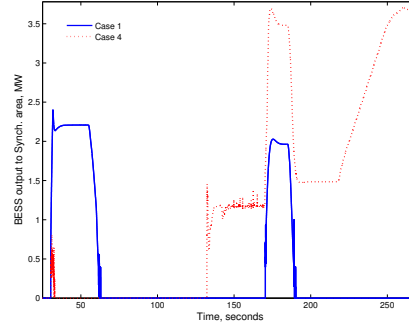
277 As shown in Figure 7(b), the support provided by the battery is smooth
278 allowing a steady discharge process which extends the BESS lifetime. More-
279 over, the delivery of energy stored from wind power (i.e. offshore and onshore)
280 responding to the frequency decay at each local area is presented in Figures 7(c)
281 and 7(d). OWPCs provide some extra power, not all the reserves; whereas the
282 OWF reaches the last step on the control leading the wind farm to its maximum
283 value.

284 3.2. Case 2: Multi-terminal and offshore wind frequency support

285 Only the MT-HVDC and the OWPCs provide primary frequency support
286 depending on the frequency dead-bands in this case. Figure 8(a) illustrates
287 the frequency response in each AC area compared to the base case. As it can
288 be seen, due to the rapid and combined response of OWPCs (shown in Figure

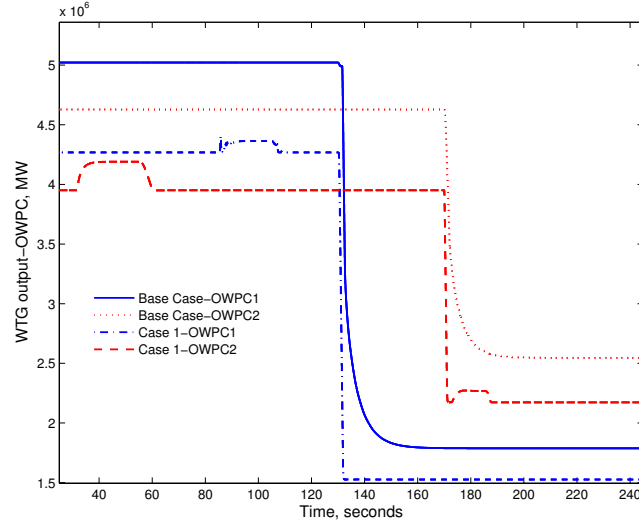


(a) Frequency responses for the different AC areas

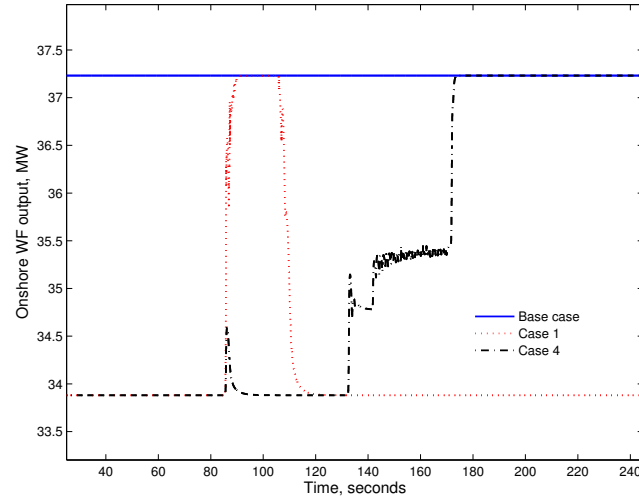


(b) Power contribution from BESS

289 8(b)), Areas 1 and 2 are capable to regain their nominal frequency (i.e. 50 Hz)
 290 under events 1 and 2. However, during the wind speed decay in both OWFCs,
 291 the wind power plants lost their potential power reserve, and the synchronous
 292 networks start to share power requirements to achieve a common frequency. It
 293 is important to remark that the frequency control for MT-HVDC networks is
 294 capable of improving the frequency steady state value of the most affected areas,
 295 although it might have a negative impact on the AC areas.



(c) Power contribution from Offshore wind farms

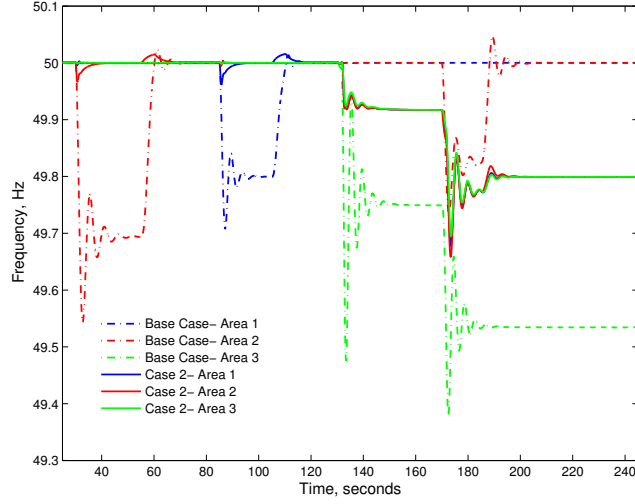


(d) Power contribution from Onshore wind farm

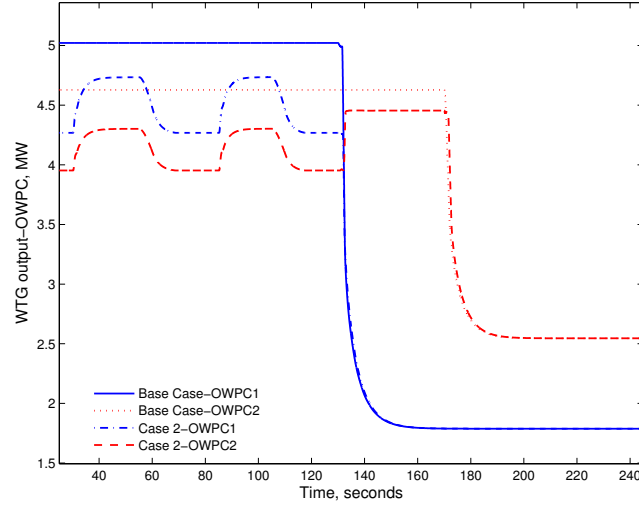
Figure 7: Simulation results obtained in Case 1 and compared with the base case

296 3.3. Case 3: OWPCs and MT-HVDC providing frequency support and BESS 297 covering power sharing gap

298 This case considers the same control as in Case 2 with the addition of the
299 BESS providing export power support only. As expected, the frequency re-



(a) Frequency responses for the different AC areas



(b) Power contribution from Offshore wind farms

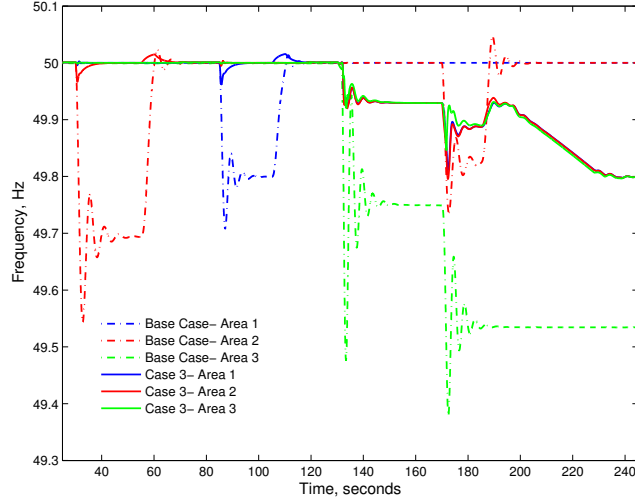
Figure 8: Simulation results obtained in Case 2 and compared with the base case

300 sponse of the different AC areas (see in Figure 9(a)) for events 1 and 2 are
 301 the same, since the OWPCs have enough reserve to cope with the power devi-
 302 ation, as illustrated in Figure 9(c). However, there is a major difference with
 303 the previous case on the frequency response for events 3, 4 and 5. In this case,

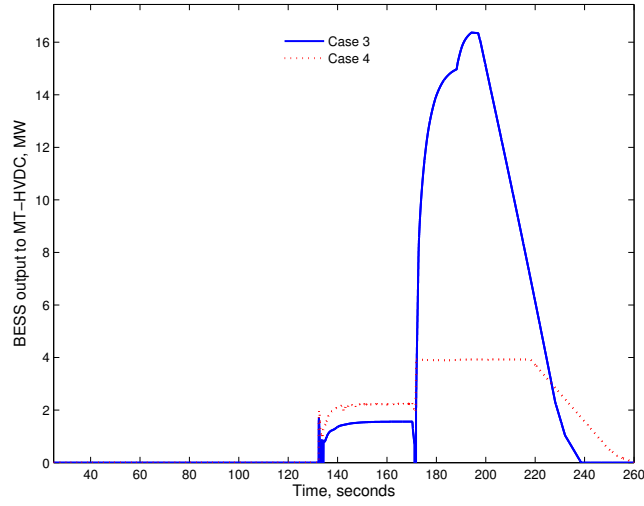
the system showed an improved response during the wind speed drops because the MT-HVDC control shares the balancing responsibilities among the AC areas. The BESS provides additional active power as it covers the gaps between the OWPCs generation and the MT-HVDC controller set-point. Likewise, the BESS covers the gap between its local AC area nominal exported power and the actual demand from the MT-HVDC. It must be noted that this contribution is possible thanks to the up-scaled converter station on Area 2. As it can be seen in Figure 9(b), the BESS largely increases its contribution under such events for ensuring frequency stability; however, after a certain time of support the BESS reaches the threshold value close to the minimum SOC and start to reduce its contribution with a constant rate. Because of this, it can be seen in Figure 9(a), that all the synchronous areas reduce their frequency (due to power reserve sharing) until the same steady state value as previously reached in Case 2. In spite of the different applied deadbands and communication delays, no serious conflicts between the implemented support methods have been recorded.

3.4. Case 4: All non-conventional power sources providing support

All support methods are considered in this case, including the two supporting modes (i.e. local and export) from the BESS. Conversely to the previous case, there exist a minor improvement achieved by the system response against Events 1 and 2 as seen in Figure 10(a). As illustrated in Figure 10(b), the OWPCs behaviours are the same as the ones on Cases 2 and 3. The improvement obtained in the frequency response in events 1 and 2 is mainly related to the contribution provided by the BESS and the OWF for providing frequency support locally to their AC area. It is worth noting that the coordination among the different technologies for providing frequency support globally, allows to reduce the local support requirement. As it is shown in Figures 7(b) and 7(d), the response of BESS and OWF in case 4 is much lower than in case 1 for the events 1 and 2, respectively. As in the previous case, the main improvement and differences appear when the OWPCs production drops. In this case, when the offshore wind speed goes down, the BESS and the OWF start to contribute as

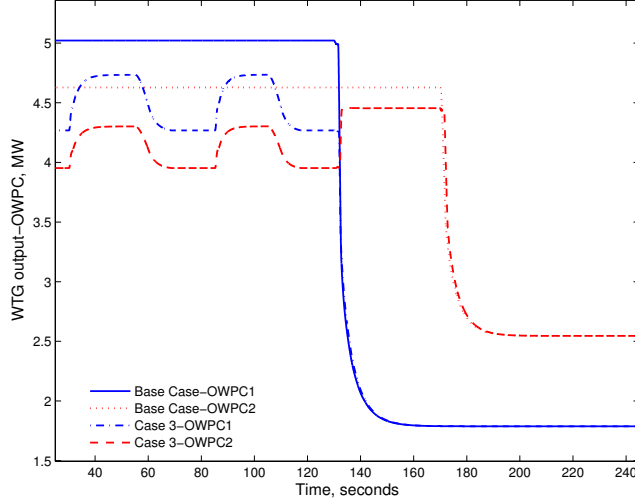


(a) Frequency responses for the different AC areas



(b) MT-HVDC power balancing from BESS

334 presented in Figures 7(b) and 7(d). This response leads to an improved steady-
 335 state frequency of the synchronous areas by reducing the power sharing needs
 336 for balancing. Moreover, in this case the converter station of Area 2 is not up-
 337 scaled, hence the BESS contribution is limited. According to that saturation,
 338 the consensus algorithm applied to the MT-HVDC do not get a common value,



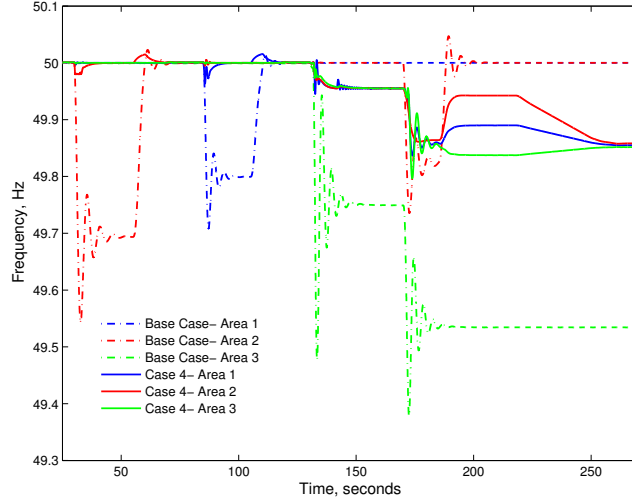
(c) Power contribution from Offshore wind farms

Figure 9: Simulation results obtained in Case 3 and compared with the base case

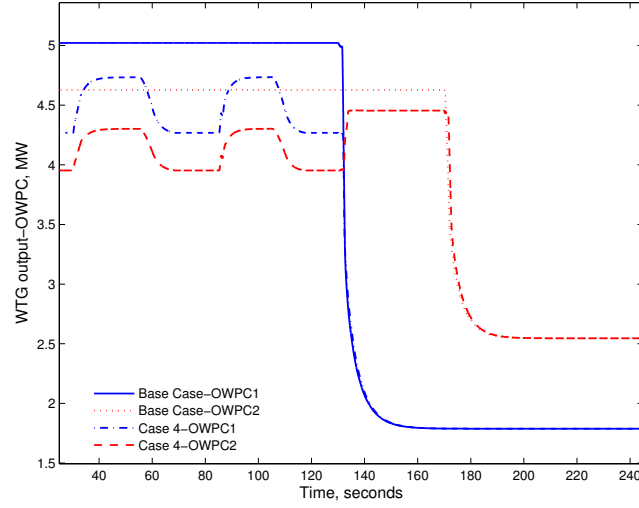
339 because the control is requiring an amount of power that the area is not capable
 340 to provide. Finally, as occurred in case 3, the BESS reduces its contribution to 0
 341 once the fixed threshold for SOC is reached. This power removal from the BESS
 342 allows the MT-HVDC control to find a new common steady-state frequency, as
 343 seen in the right side of Figure 10(a). It is of note that the consensus has not
 344 been reached, not due to a malfunction in the holistic controller but the con-
 345 verter station capacity does not allow the execution of the provided set-point
 346 by the controller. Hence, the power imbalance sustains causing a steady state
 347 frequency deviation at this area, which is not similar to the other two areas.

348 In order to evaluate the relevance of a proper selection of the frequency
 349 deadband setting, the previous case study is reproduced, whereby the same
 350 deadband, namely 20 mHz, is applied to all non-conventional power sources
 351 providing support. As can be seen in Figures 11(a) and 11(b), an oscillatory
 352 response is obtained due to the interaction of all the systems supporting the
 353 frequency at the same time.

354 Analysing the full picture of the executed case studies, it is noticed that the



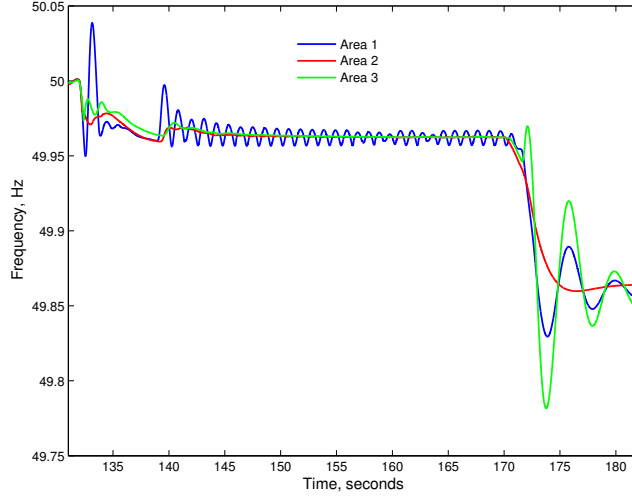
(a) Frequency responses for the different AC areas



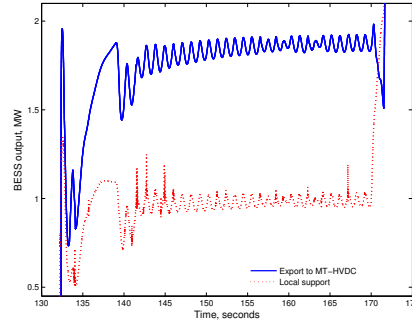
(b) Power contribution from Offshore wind farms

Figure 10: Simulation results obtained in Case 4 and compared with the base case

355 risk of violating grid codes is high when the non-conventional power sources are
 356 not integrated. It can be highlighted that the foreseen scenario of the inter-
 357 connected AC areas with non-conventional power sources in Case 4 presented a
 358 smooth and beneficial coordination between the different control methods and



(a) Frequency responses for the different AC areas



(b) Power contribution from BESS

Figure 11: Case 4 with similar frequency deadband applied for all the integrated frequency support controllers

359 their assigned power sources, during severe events leading to better frequency
 360 response. Thus, the adequate selection of frequency dead-bands is a key step
 361 for proper control coordination. Also, it can be extracted that the rated power
 362 of converter station of the AC area is of major relevance to the potential shared
 363 contribution. In particular, the insufficient size of the power converter will re-
 364 strict the potential contributions from BESS and OWF as well as limit the
 365 frequency consensus regulated by the MT-HVDC controller.

366 4. Conclusion

367 The foreseen interactions between different synchronous areas that are con-
368 nected to a MT-HVDC grid imply many challenges to the stability of these areas
369 and the optimum coordination between the different generation assets.

370 The conducted research work has evaluated and coordinated different pro-
371 posed control methods for frequency stability support developed for various
372 power-electronic based technologies such as MT-HVDC, onshore and offshore
373 wind power as well as energy storage. The paper has focused on the potential
374 coordination and interaction among such technologies for providing primary
375 frequency support, taking into consideration some technical limitations and re-
376 strictions as dead-bands and communication delays.

377 It has been shown that system security and stability may be improved as long
378 as the quantity of frequency support (i.e. power reserves or sharing capacity)
379 is increased. It has been presented that the frequency support provision can
380 be managed carefully through the coordinated MT-HVDC controller; however,
381 some parameters must be carefully selected as dead-band, converter station
382 sizing and energy storage to be installed. It is worth noting that, although
383 each controller has been designed to operate alone, the conflicts between the
384 different controllers operating together have been very limited ensuring system
385 stability. This has been achieved through the proper selection of the frequency
386 dead-bands providing control preference.

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